

*MARSCHER / GRANT / CR*  
*IN-89*

**Title of Grant:** Theoretical Interpretation of the HEAO-3  
Observations of Cygnus X-3 Under the  
HEAO-3 Guest Investigator Program

*85364*

*P9*

**Final Technical Report**

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**Grant Period:** July 1, 1985 to June 30, 1987

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**Grant Number:** NAG8-537

(NASA-CR-181171) THEORETICAL INTERPRETATION  
OF THE HEAO-3 OBSERVATIONS OF CYGNUS X-3  
UNDER THE HEAO-3 GUEST INVESTIGATOR PROGRAM  
Final Technical Report, 1 Jul. 1985 - 30  
Jun. 1987 (Boston Univ.) 9 p Avail: NTIS G3/89

N87-25905

Unclassified  
0085364

The project objective was to develop a theoretical framework for understanding the wide variety of extreme emission from the galactic X-ray binary Cygnus X-3. The main characteristic of the source is its time variable X-ray emission, the flux of which oscillates with a 4.8 hour period. Extremely high energy  $\gamma$ -rays and variable, nonthermal radio emission are also detected from Cygnus X-3.

From the onset of the project, it was clear that published models for the source were totally inadequate. The X-ray oscillations were imagined to be caused by obscuration by a scattering medium which revolved about the source with the period of the binary system, presumed to be 4.8 hours. The 4.8 hour period itself requires an extremely tight binary orbit, with orbital diameter only about as large as the diameter of a star similar to the sun. It is then difficult to understand why the most extreme X-ray object in the galaxy contains nothing more exotic than a neutron star in orbit with a normal, main-sequence star. In addition, the energy dependence of the X-ray flux modulation indicated that scattering, which is energy independent for medium-energy X-rays, could not cause the modulation.

Because of these deficiencies of the earlier models, it was decided to develop a model along the lines of those known to explain the X-ray system SS 433. In this source, which is not blocked out in the optical by dust as is Cygnus X-3, the optical emission line variations indicate that two oppositely directed jets with speeds of  $0.26c$  are generated from the central compact star. The jets precess with a period of 164 days. If, in Cygnus X-3, the jets were twice as fast, about  $0.5c$  (as was later verified by radio VLBI observations), the X-ray modulation could then be caused by relativistic beaming which changes as the precessing jets change their angles relative to the line of sight. A complete model was developed, with the prediction that, as in SS 433, any X-ray lines should shift in energy as the jets precess. As we were writing the paper describing this model, an observational paper on the EXOSAT results for Cygnus X-3 appeared (van der Klis *et al.*, *Space Science Reviews*, **40**, 297) which showed that this prediction is not fulfilled. Rather, the energy of the detected iron line shifts only slightly in energy, and in the opposite sense from that predicted.

The theoretical model had to be modified in light of this new information. The speed of the jet (whose presence was in fact verified by radio VLBI observations) cannot be relativistic even though the radio observations show speeds of about  $0.5c$ . Instead, either apparent speeds of  $0.5c$  would have to be produced by the precession of the jets, or the X-rays are not produced in the jet at all, but rather in the accretion disk surrounding the compact star. A model along these lines has been developed by the P.I. and his graduate student, John Travis. A draft of a paper to be submitted to *Nature* is attached. The draft contains further information on the latest version of the model for Cygnus X-3.

Signed,



Alan P. Marscher  
Principal Investigator

Draft of paper to be sent to *Nature*

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The galactic X-ray source Cyg X-3 is the most extreme object of its kind. It is one of the most luminous X-ray sources in the galaxy, with an X-ray flux which modulates with a 4.8 hour period. Cyg X-3 emits  $\gamma$ -rays up to at least  $10^{15}$  eV, and could be the sole source of the highest energy cosmic rays found in the galaxy. The radio emission is nonthermal, fluctuates with a 4.95 hour period, and occasionally explodes in outbursts of over a factor of 10 in flux density. VLBI observations indicate that the radio emission arises in a jet moving at a speed in the plane of the sky of about  $0.35c$ . In this respect it is similar to SS 433 and extragalactic radio sources.

Past models for Cyg X-3 rely on variable electron scattering to explain the modulation of the X-ray flux. This conflicts with the observed energy dependence of the modulation: the modulation decreases with increasing X-ray energy. This behavior is more consistent with photoelectric absorption or with a two-component emission model in which the hard component is steady.

The 4.8 hour period of Cyg X-3 has long been considered to be the orbital period of the presumed binary system. This implies an orbital radius of only  $10^{11}$  cm, which is comparable to the *radius* of a main sequence star. However, it seems to us unlikely that the most extreme X-ray source in the galaxy would be caused by the interaction between an ordinary star and a collapsed object. Also, the 4.95 hour period observed in the radio indicates that there is another period involved which “beats” with the 4.8 hour period to produce the longer radio period.

Here we deviate from these previous models by assuming that the X-rays originate in a jet (similar to the observed situation in SS 433). It is then possible for the 4.8-hour period to be caused by variable absorption which occurs as the jet precesses. The period

is therefore a precession period rather than an orbital period. The orbital period can be significantly longer than this. An alternate possibility, that the X-ray modulation could be caused by variable doppler beaming by a semi-relativistic jet which precesses with a 4.8 hour period, can be eliminated by the measurements of the X-ray iron line frequency as a function of phase (van der Klis *et al.* 1985). The lack of substantial frequency oscillation of the line limits any jet velocity to less than about  $0.01c$ . We therefore consider the source of the 4.8 hour modulation of x-rays from Cyg X-3 not to be the orbital period of a binary system, but rather the precession period of an accretion disk and jet.

The blobs of material making up the jet must be luminous for a period of time shorter than the 4.8 hour modulation period in order to cause the given depth of modulation seen in the light curve. Take the luminosity duration to be  $10^3 - 10^4$  s. Then the distance the blobs travel while being luminous is  $3 \times 10^{11} - 3 \times 10^{12}$  cm. If we assume that the blobs are luminous right from the time of their creation, then they disappear while still in the outer regions of the accretion disk corona ("ADC"). Therefore, in order to determine the luminosity of the source as a function of time, it is necessary to include the effects of absorption on the received flux of the X-rays as they pass through the ADC.

Most authors who invoke an ADC to explain the modulation of the Cyg X-3 radiation use the ADC as a scattering region, whereby the radiation from the central source is scattered into the line of sight, giving the appearance of an extended x-ray source. This extended source is then eclipsed by one or more turbulent bulges along the rim of the disk, caused by the interaction of the stream of material falling off the mass-losing star onto the accretion disk. As a result, these eclipses have the same period as the orbital period of the binary system. Furthermore, the geometry of these bulges is not known, offering great freedom in the modelling process when trying to fit the observed X-ray light curve.

We may suppose instead that the primary role of the ADC is not to make the X-ray source appear extended by scattering radiation into the line of sight, but rather to make the observed intensity of a blob appear dimmer by absorption. In order to find the magnitude of this effect, we need to consider how the density of the ADC varies as a function of position. The usual method is to balance the gas pressure in the corona with the vertical gravitational pull from the central star (the disk itself is assumed to have only an insignificant mass), while the horizontal gravitational pull on a parcel of gas in the corona is balanced by a Keplerian orbit. This approximation gives an exponential dependence of the density on height above the disk at a given radius. Unfortunately, this analysis breaks down when the height above the disk is of the same order of magnitude as the distance along the disk from the center. This limits the usefulness of the analysis to viewing angles within only small angles to the plane of disk. Furthermore, if the jet describes a reasonably narrow cone about the precession axis, then the height of any given blob above the disk will be greater than the corresponding radius from the center of the disk, putting the blob in a region of the corona which is not well represented by the standard form of the density profile. Thus this approximation cannot describe precession of relatively large angles nor relatively small angles.

The above derivation of the positional dependence of the density of the ADC also depends on the assumption that we have a static disk. This may not be such a bad approximation for a precessing disk, for if we assume reasonable parameters, the rim of the disk may have a maximum velocity of around 30 km/s, a couple of orders of magnitude lower than the sound speed in an ADC having a temperature around  $7 \times 10^7$  K and density of a few  $\times 10^{14}$  g cm<sup>-3</sup>.

We may avoid some of the complications if we assume that only the inner regions of the disk are precessing. This is likely to be the case anyway, for the period of a parcel of gas around  $10^{11}$  cm to orbit the central star is on the order of 4 hours, while the

precession period is taken to be 4.8 hours. Precession periods are usually significantly greater than the periods of rotation, so those regions in the disk which orbit with periods much lower than the 4.8 hour precession period must be where the precession occurs. We therefore ignore the complications due to whole-disk precession and use the density profiles of McClintock *et al.* to derive the optical depth through the ADC for several blobs of material seen at some angle to the line of sight. We can derive a modulation similar to that observed for reasonable densities and opening angles of precession.

Asymmetry in the light-curve is introduced by the extension of the emitting material over a large region as the blobs move ballistically. The blobs change luminosity with distance from the source, and appear to wrap around the precession axis as a portion of a conical helix. As the jet precesses, it will appear to be "swept back" as the source rotates out from under the blobs previously emitted. This will lead to very different intensities measured at corresponding angles of the jet to the line of sight, thus producing the observed asymmetry.

The observed frequency dependence on the depth of modulation is naturally explained by this model. Higher frequency x-rays are absorbed less efficiently by the material in the corona. This yields smaller differences in optical depth as a function of position within the corona for higher frequency x-rays, and hence a relatively shallower light curve. The relative timing of the rises and dips in the light curve for different frequencies is highly parameter-dependent.

In the quiescent state, Cygnus X-3 has been observed to have radio emission with a period slightly but detectably longer than its 4.8 hour period at higher energies. The radio source subtends an angle of  $\sim 1$  mas, corresponding to a size of something greater than  $10^{14}$  cm if Cyg X-3 lies at a distance of 12 kpc. It is possible to explain the origin of the radio emission as the interaction of a subrelativistic jet of material from an accreting member of a binary system with a shell of material at around  $10^{14}$  cm.

The x-rays are produced in this jet thermally near the source and are modulated at 4.8 hours by precession of the jet, while the radio period is a result of the addition of the jet velocity and the orbital velocity of the compact star, and so is not expected to remain constant with orbital phase.

The orbital velocity of the compact star, assuming a circular orbit, is

$$V_{orb} = M_2 \left[ \frac{2\pi G}{(M_1 + M_2)^2 P_{orb}} \right]^{1/3},$$

where  $M_1$  is the mass of the compact star,  $M_2$  is the mass of the secondary, and  $P_{orb}$  is the period of the orbit. Suppose the compact star has about it an accretion disk and a jet, both of which precess about an axis with period  $P_{X-ray}$ , and that the velocity of the material in the jet is  $v_{jet}$ . Further suppose that at some time  $t$  the jet lies at an angle  $\theta$  with the orbital velocity in the reference frame of the accreting star. In an external frame, the resultant velocity of the jet material is

$$v_{res} = (v_{orb}^2 + v_{jet}^2 - 2v_{orb}v_{jet} \cos \theta)^{1/2},$$

and the corresponding angle  $\theta'$  is such that

$$\cos \theta' = (v \cos \theta_{jet} - v_{orb}) / v_{res}$$

and

$$\sin \theta' = (v_{jet} \sin \theta) / v_{res}.$$

If we take  $P_{orb}$  to be much larger than  $P_{X-ray}$ , then at a time  $t + P_{X-ray}$ , the jet will again form an angle  $\theta$  with the orbital velocity, again having the resultant velocity  $v_{res}$  at angle  $\theta'$ . In this time, the compact star has moved a distance  $v_{orb}P_{X-ray}$ , and lies a distance  $v_{orb}P_{X-ray} \cos \theta'$  farther from the material to be shocked at  $10^{14}$  cm. Therefore, the radio period caused by the jet when it is at an angle  $\theta$  to the orbital

velocity is

$$P_{rad} = P_{X-ray} = (v_{orb} P_{X-ray} \cos \theta') / v_{res},$$

or

$$P_{rad}/P_{X-ray} = \frac{(v_{jet}^2 - v_{jet} v_{orb} \cos \theta)}{(v_{jet}^2 + v_{orb}^2 - 2v_{jet} v_{orb} \cos \theta)}.$$

As the jet precesses,  $\theta$  varies from some  $\theta_{min}$  to  $\theta_{max}$ , so there will be a very complicated dependence of the radio emission with time, but the dominant influence will be from the angle  $\theta$  at which the jet lies closest to the line of sight.

To get an order-of-magnitude feeling for the properties of this system, take  $M_1 = 0.5M_0$ ,  $M_2 = 4M_0$ , and  $P_{orb} = 8$  days. Then  $v_{orb} = 156.5$  km/s. If  $P_{X-ray}$  is 4.8 hours and  $P_{rad} = 4.95$  hours at  $\theta = 20^\circ$ , then  $v_{jet} = 4830$  km/s, or about  $1.6 \times 10^{-2}c$ . In the X-ray spectrum there is an iron emission line whose centroid energy varies sinusoidally between 6.67 keV and 6.75 keV during the 4.8 hour period. If we interpret this as a doppler shift, then

$$\frac{(1 - b \cos a_{max})}{(1 - b \cos a_{min})} = \frac{6.75 \text{keV}}{6.67 \text{keV}},$$

where  $a_{min}$  is the minimum angle between the jet and the line of sight, and  $a_{max}$  is the maximum angle between the jet and the line of sight. If  $b = 1.6 \times 10^{-2}$ , then

$$\cos a_{min} = 1.012 \cos a_{max} + 0.744,$$

so that if, for example,  $a_{max} = 80^\circ$ ,  $a_{min} = 23^\circ$ .

Radio measurements of Cyg X-3 have shown that it appears to be expanding at moderately relativistic speeds. This could be an illusion caused by the point at which the jet intercepts the enshrouding material moving relativistically as the jet precesses some  $10^{14}$  cm inside.

It therefore appears that a reasonable model for the Cyg X-3 system can be devised in which the 4.8 hour period is a precession period of the jet. The precession

would presumably be that of the inner accretion disk, which would have a period much shorter than 4.8 hours. The actual binary orbital period is therefore not constrained to be 4.8 hours, which allows the secondary star to be a supergiant, as is indicated by the luminosity of the system. This alternative model should prove helpful in the interpretation of the Cyg X-3 system, especially in relation to the production of the radio outbursts and the very high energy  $\gamma$ -rays.